GIS-BASED HYDROLOGIC MODELING:
THE AUTOMATED GEOSPATIAL WATERSHED ASSESSMENT TOOL

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Abstract: Planning and assessment in land and water resource management are evolving toward complex, spatially explicit regional assessments. These problems have to be addressed with distributed models that can compute runoff and erosion at different spatial and temporal scales. The extensive data requirements and the difficult task of building input parameter files, however, have long been an obstacle to the timely and cost-effective use of such complex models by resource managers. The USDA-ARS Southwest Watershed Research Center, in cooperation with the U.S. EPA Landscape Ecology Branch, has developed a geographic information system (GIS) tool to facilitate this process. A GIS provides the framework within which spatially distributed data are collected and used to prepare model input files and evaluate model results. The Automated Geospatial Watershed Assessment tool (AGWA) uses widely available standardized spatial datasets that can be obtained via the internet. The data are used to develop input parameter files for KINEROS2 and SWAT, two watershed runoff and erosion simulation models that operate at different spatial and temporal scales. AGWA automates the process of transforming digital data into simulation model results and provides a visualization tool to help the user interpret results. The utility of AGWA in joint hydrologic and ecological investigations has been demonstrated on such diverse landscapes as southeastern Arizona, southern Nevada, central Colorado, and upstate New York.

INTRODUCTION

The accurate depiction of earth surface processes and their responses to land cover, climate, or managerial change has been the goal of research hydrologists for more than a century. As the science has evolved, fully integrated watershed assessment tools for support in land management and hydrologic research are becoming established tools in both basic and applied research. At the core of many of these tools are spatially distributed hydrologic models because they provide a mechanism for investigating interactions among climate, topography, vegetation, and soil as they affect watershed response. Spatially distributed models are by definition data-intensive, and if these models are to be applied on an operational basis, there is a critical need for automated PC-based procedures to store, access, and prepare data for modeling.

This manuscript presents the Automated Geospatial Watershed Assessment (AGWA) tool, a multipurpose hydrologic analysis system for use by watershed, natural resource, and land use managers and scientists in performing watershed- and basin-scale studies. It was developed under the following guidelines:

1. Provide a simple, direct, and repeatable method for hydrologic model parameterization
2. Use only basic, attainable GIS data

3. Be compatible with other geospatial watershed-based environmental analysis software
4. Be useful for scenario and alternative futures simulation work at multiple scales.

AGWA is an extension for the Environmental Systems Research Institute's ArcView versions 3.X (ESRI, 2001), a widely used and relatively inexpensive PC-based GIS software package (trade names are mentioned solely for the purpose of providing specific information and do not imply recommendation or endorsement by the USDA). The GIS framework is ideally suited for watershed-based analysis, which relies heavily on landscape information for both deriving model input and presenting model results. In addition, AGWA shares the same ArcView GIS framework as the U.S. EPA Analytical Tool Interface for Landscape Assessment (ATtILA; Ebert *et al.*, 2000), and Better Assessment Science Integrating Point and Nonpoint Sources (BASINS; Lahlou *et al.*, 1998). This facilitates comparative analyses of the results from multiple environmental assessments, thus making it particularly valuable for interdisciplinary studies, scenario development, and alternative futures simulation work. AGWA is distributed freely via the internet as a modular, open-source suite of programs (www.tucson.ars.ag.gov/agwa).

AGWA provides the functionality to conduct all phases of a watershed assessment for two widely used watershed hydrologic models: the Soil Water Assessment Tool (SWAT; Arnold *et al.*, 1994); and a customized version of the KINEmatic Runoff and erOSion model (KINEROS2; Smith *et al.*, 1995). SWAT is a continuous simulation model for use in large (river-basin scale) watersheds. KINEROS2 is an event-driven model designed for small arid, semi-arid, and urban watersheds. The AGWA tool combines these models in an intuitive interface for performing multi-scale change assessment, and provides the user with consistent, reproducible results. Data requirements include elevation, land cover, soils, and precipitation data, all of which are available at no cost over the internet. Model input parameters are derived directly from these data using optimized look-up tables that are provided with the tool.

OVERVIEW OF THE AGWA TOOL

The conceptual design of AGWA is presented in Figure 1. A fundamental assumption of AGWA is that the user has previously compiled the necessary GIS data layers, all of which are easily obtained for the conterminous United States. The AGWA extension for ArcView adds the 'AGWA Tools' menu to the View window, and must be run from an active view. Pre-processing of the DEM to ensure hydrologic connectivity within the study area is required, and tools are provided in AGWA to aid in this task. Once the user has compiled all relevant GIS data and initiated an AGWA session, the program is designed to lead the user in a stepwise fashion through the transformation of GIS data into simulation results. The AGWA Tools menu is designed to reflect the order of tasks necessary to conduct a watershed assessment, which is broken out into five major steps: (1) location identification and watershed delineation; (2); watershed subdivision by (3) land cover and soils parameterization; (4) preparation of parameter and rainfall input files; and (5) model execution and visualization and comparison of results.

Step 1: The user first creates a watershed outline, which is a grid based on the accumulated flow to the designated outlet (pour point) of the study area. If a GIS coverage of the outlet location exists (such as would be the case for a runoff gauging station), it can be used to designate the drainage outlet. Alternatively, the user has the option of using a mouse to click on the watershed outlet. If internal gauging stations exist as a separate GIS coverage, AGWA will use them as internal drainage pour points and generate output at each of the stations. This option is particularly useful for calibration and validation of model results.

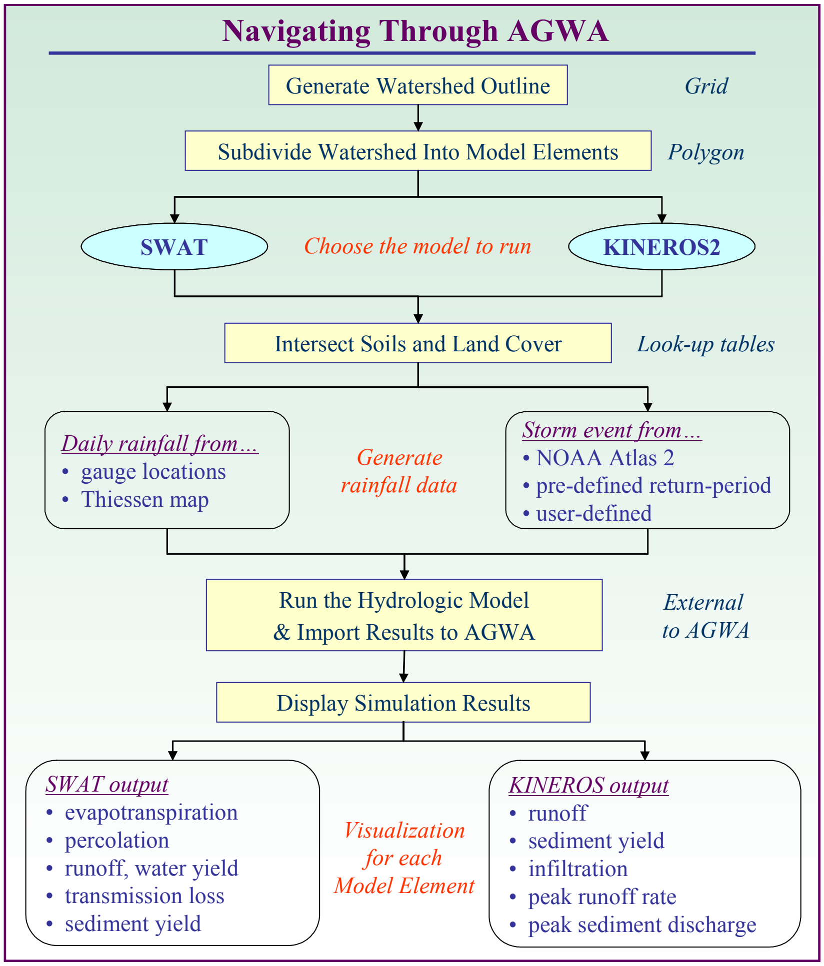

Figure 1. Sequence of steps in the use of AGWA for hydrologic modeling.

Step 2: A polygon shapefile is built from the watershed outline grid created in step 1. The user specifies the threshold of contributing area for the establishment of stream channels, and the watershed is divided into model elements required by the model of choice. From this point onward, tasks are specific to the model that will be used (KINEROS2 or SWAT), but the same general process is followed independent of model choice.

Step 3: The watershed created in Step 2 is intersected with soil and land cover data, and parameters necessary for the hydrologic model runs are determined through a series of GIS analyses and look-up tables. The hydrologic parameters are added to the polygon and stream channel tables to facilitate the generation of input parameter files. At this point the user can manually alter parameters for each model element if additional information is available to guide the estimation of those values.

Step 4: Rainfall input files are built at this stage. For SWAT, the user must provide daily rainfall values for rainfall gages within and near the watershed. If multiple gages are present, AGWA will build a Thiessen polygon map and create an area-weighted rainfall file. For KINEROS2, the user can select from a series of pre-defined rainfall events dependent on the geographic location, choose to build his/her own rainfall file through an AGWA module, or use NOAA Atlas II return period rainfall depth grids distributed with AGWA (NOAA, 1973). Precipitation files may be created for uniform (single gauge) or distributed (multiple gauge) rainfall data.

Step 5: After Step 4, all necessary input data have been prepared: the watershed has been subdivided into model elements; hydrologic parameters have been determined for each element; and rainfall files have been created. The user can proceed to run the hydrologic model of choice. AGWA will automatically import the model results and add them to the polygon and stream map tables for display. A separate module controls the visualization of model results. The user can toggle among viewing various model outputs for both upland and channel elements, enabling the problem areas to be identified visually. If multiple land cover scenes exist, the user can parameterize either or both of the two models and attach the results to a given watershed. Results can then be compared on either an absolute or percent change basis for each model element (Miller *et al.*, 2002). Model results can also be overlaid with other digital data layers to further prioritize management activities.

COMPONENT MODELS

The key components of AGWA are the hydrological models used to evaluate the effects of land cover and land use on watershed response. In this section, a description of the basic structure of each model is provided as well as their simplifying assumptions, strengths, and weaknesses. The KINEROS2 and SWAT models are able to simulate complex watershed representations in order to explicitly account for spatial variability of soils, rainfall distribution patterns, and vegetation.

KINEROS2: KINEROS2 is an event-oriented, physically based model describing the processes of interception, infiltration, surface runoff, and erosion from small agricultural and urban watersheds (Smith *et al.*, 1995). In this model, watersheds are represented by subdividing contributing areas into a cascade of one-dimensional overland flow and channel elements using topographic information. KINEROS2 is a broadly updated version of KINEROS that is now incorporated into AGWA (see Goodrich *et al.*, this volume).

In numerous modeling studies, the KINEROS model has been applied on the USDA-ARS Walnut Gulch Experimental Watershed (Renard *et al.*, 1993), a semi-arid watershed with 11 nested subwatersheds that range in area from 2.3 to 148 km^2, and an additional 13 small watershed areas ranging from 0.004 to 0.89 km^2. Spatial variability in rainfall is measured using a network of 89 gauges. At a small scale, Goodrich *et al.* (1995) and Faures *et al.* (1995) applied KINEROS to the 4.4 km^2 Lucky Hills (LH-104) subwatershed to examine the importance of different antecedent soil moisture estimates and the effects of wind and rainfall pattern on the predicted discharges. At this scale, both studies conclude that an adequate representation of the rainfall pattern is crucial to achieve accurate runoff prediction in this environment. Goodrich *et al.* (1994) also investigated the sensitivity of runoff production to the pattern of antecedent moisture condition at the small watershed scale (6.31 km^2). They suggested that a simple basin average of initial moisture content will normally prove adequate and that, again, knowledge of the rainfall patterns is far more important. Michaud and Sorooshian (1994) compared three different models at the scale of the whole watershed, a lumped curve number model, a simple distributed curve number model, and the more complex distributed KINEROS model. The modeled events were 24 severe thunderstorms with a rain gage density of one per 20 km^2. Their results suggested that none of the models could adequately predict peak discharge and runoff volumes, but that the distributed models did somewhat better in predicting time to runoff initiation and time to peak. The lumped model was, in this case, the least successful.

Goodrich *et al.* (1997) used data from the entire Walnut Gulch watershed to investigate the effects of storm area and watershed scales on runoff coefficients. They concluded that, unlike humid areas, there is a tendency for runoff response to become more nonlinear with increasing watershed scale in this type of semi-arid watershed as a result of the loss of water into the bed of ephemeral channels and the decreasing relative size of rainstorm coverage with watershed area for any individual event. According to Syed (1999), using standard USGS 30m DEMs to model runoff from a medium size watershed (~100 km^2) with the kinematic wave approximation yields acceptable simulation results. For watersheds of this size, this implies that USGS level I, 30m DEM data, such as are available throughout the continental United States, are adequate. For smaller watersheds of the order of several hectares better vertical accuracy is desired especially when using high horizontal resolution (small grid spacing) DEMs.

SWAT: SWAT is a river-basin, or watershed-scale model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields on large, complex watersheds with varying soils, land use, and management conditions over long periods of time (Arnold *et al.*, 1994). The model combines empirical and physically-based equations, uses readily available inputs, and enables users to study long-term impacts. SWAT is defined by eight major components: hydrology, weather, erosion and sedimentation, soil temperature, plant growth, nutrients, pesticides and land management.

SWAT is currently being utilized in several large basin projects. SWAT provides the modeling capabilities of the HUMUS (Hydrologic Unit Model of the United States) project (Srinivasan *et al.*, 1993). The HUMUS project simulates the hydrologic budget and sediment movement for the approximately 2,100 hydrologic unit areas that have been delineated by the USGS. Findings of the project are being utilized in the Resource Conservation Act (RCA) appraisal conducted by the Natural Resources Conservation Service. Scenarios include projected agricultural and municipal water use, tillage and cropping system trends, and fertilizer and animal waste use management options. The model is also being used by NOAA to estimate nonpoint source loadings into all U.S. coastal areas as part of the National Coastal Pollutant Discharge Inventory. The U.S. EPA is currently incorporating SWAT into the BASINS interface for assessment of impaired water bodies.

SWAT uses the curve number approach to predict runoff generation and it has been the subject of a number of critical reviews (e.g. Hjelmfelt *et al.*, 1982; Bales and Betson, 1982). Further work is required to clarify under what conditions the method gives satisfactory predictions. Mishra and Singh (1999) show that their generalized version of the method gives better results than the original formulation, as it should, since it has two additional fitting parameters.

Hjelmfelt *et al.* (1982) found no strong correlation between curve number and antecedent condition for individual rainfall events, suggesting that interactions with individual storm characteristics, tillage, plant growth and temperature were sufficient to mask the effect of antecedent rainfall. Despite its limitations, the Curve Number method has been used quite widely since it provides a relatively easy way of moving from soil and vegetation data sets (such as in GIS) to a rainfall-runoff model.

DATA INPUTS AND PARAMETER ESTIMATION

Watershed Discretization: Over the past decade numerous approaches have been developed for automated extraction of watershed structure from grid digital elevation models (e.g. Mark *et al.*, 1984; Band, 1986; Moore *et al.*, 1988; Martz and Garbrecht, 1993). The most widely-used method, and that which is used in AGWA, for the extraction of stream networks is to accumulate the channel source area (CSA) upslope of each pixel through a network of cell-to-cell drainage paths. This network is subsequently pruned based on a threshold drainage area required to define a channel. The watershed is then further subdivided into upland and channel elements as a function of the stream network density. In this way, a user-defined CSA is used to define the locations and numbers of stream channels; since the watershed is subdivided into upland and channel elements as a function of the stream channels, the choice of CSA is the determining factor in the spatial complexity of the watershed discretization. This approach often creates a large number of spurious polygons and disconnected model elements due to vagaries in the underlying DEM. A suite of algorithms has been implemented in AGWA that refines the watershed elements by eliminating spurious elements and ensuring downstream connectivity.

Parameter Estimation: Each of the plane and channel elements delineated by AGWA is represented in either SWAT or KINEROS2 by a set of parameter values. These values are assumed to be uniform within a given element. There may be a large degree of spatial variability in the topographic, soil, and land cover characteristics within the watershed, and AGWA uses an area-weighting scheme to determine an average value for each parameter within an overland flow model element abstracted to an overland flow plane (Goodrich *et al.*, this volume). As shown in Figure 2, the three GIS coverages are intersected with the subdivided watershed, and a series of look-up tables and spatial analyses are used to estimate parameter values for the unique combinations of land cover and soils. SWAT and KINEROS2 require a host of parameter values, and estimating their values can be a tedious task; AGWA rapidly provides estimates based on an extensive literature review and calibration efforts. In the absence of observed data and performing a calibration exercise, these values should be used in comparative or relative assessments. Since AGWA is an open-source suite of programs, users can modify the values of the look-up tables or manually alter the parameters associated with each element.

Soil parameters for upland planes as required by KINEROS2 (such as percent rock, suction head, porosity, saturated hydraulic conductivity) are initially estimated from soil texture according to the STATSGO soil data following Woolhiser *et al.* (1990) and Rawls *et al.* (1982). Saturated hydraulic conductivity is reduced following Bouwer (1966) to account for air entrapment. Further adjustments are made following Stone *et al.* (1992) as a function of estimated canopy cover. Cover parameters, including interception, canopy cover, Manning's roughness, and percent paved area are estimated following expert opinion and previously published look-up tables (Woolhiser *et al.*, 1990). Examples of these look-up values for the North American Landscape Characterization classification scheme of the Upper San Pedro Basin in southern Arizona are shown in Table 1. Upland element slope is estimated as the average plane slope, while geometric characteristics such as plane width and length are a function of the plane shape assuming a rectangular shape, where the longest flow length is equal to element length. Stream channels geometric characteristics are parameterized following Miller *et al.* (1995), who found strong relationships between channel width and depth and watershed characteristics. Channel parameters relating to soil characteristics assume a sandy bed and all channels are assumed uniform. Channel slope is determined from a slope grid derived from the DEM.

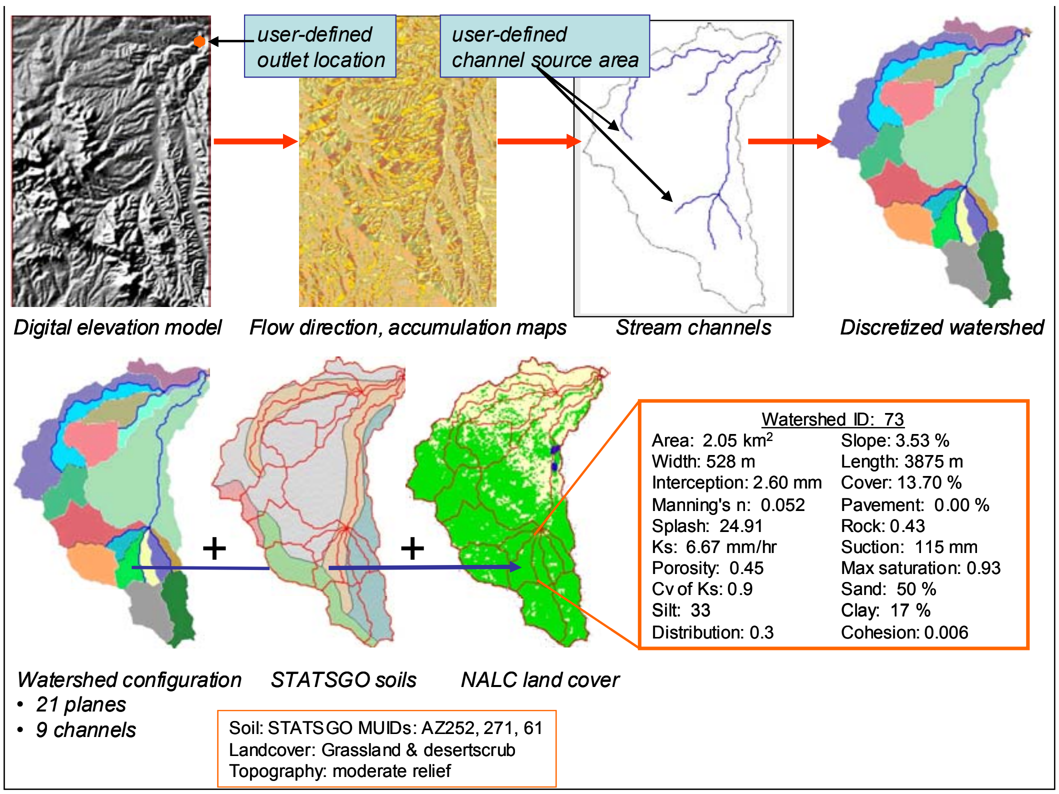

Figure 2. The transformation of topography, soils, and land cover GIS data into KINEROS2 input parameters. A DEM is used to subdivide the watershed into upland and channel model elements, each of which are parameterized according to their soil, topographic, and land cover characteristics.

Similar approaches are used to provide estimates for soil and land cover parameters as required by SWAT. The most sensitive parameter of SWAT is the Curve Number, which is estimated as a function of hydrologic group, hydrologic condition, cover type, and antecedent moisture condition. STATSGO data provide information on soil hydrologic group, while cover type is determined from classified land cover data. AGWA assumes a fair hydrologic condition, and antecedent moisture group II. Look-up tables following USDA-SCS (1986) recommendations are used to estimate Curve Number values for each unique combination of hydrologic group and land cover type within a watershed element. Because the land cover data are grids, this process occurs for each cell, and the results are area-weighted to produce a unique estimate of Curve Number for the overland flow plane (Table 2).

Table 1. Portion of the look-up table for NALC land cover used by AGWA for the estimation of upland element parameters for KINEROS2 (based on expert opinion and Woolhiser *et al.*, 1990).

Land Cover	Interception (mm/hr)	Canopy (%)	Manning's n
Grassland	2.0	25	0.050
Desertscrub	3.0	10	0.055
Riparian	1.15	70	0.060
Agriculture	0.75	50	0.040
Urban	0.0	0.0	0.010

Table 2. Curve Number look-up table for selected land cover types. Higher values of Curve Number correspond to higher estimates of simulated runoff (based on USDA-SCS, 1986).

Land Cover	Soil Hydrologic Group			
	A	*B*	*C*	*D*
High intensity residential	81	88	91	93
Bare rock/sand/clay	96	96	96	96
Forest		55	75	80
Shrubland	63	77	85	88
Grasslands/herbaceous		80	87	93
Small grains	65	76	84	88

Rainfall Input: A variety of methods are available in AGWA to create rainfall input files for KINEROS2 and SWAT. Each of these are described briefly below, and organized according to the models for which they are designed.

KINEROS2: Either distributed or uniform precipitation input can be used with KINEROS2, and is provided in the form of storm hyetographs for one or more point locations. Data from multiple point locations is distributed across the watershed by KINEROS2 using a piecewise planar time-space interpolation technique (Goodrich, 1991). Since the spatial component of this process is computed by the model itself, it was deemed unnecessary to prepare distributed input files in AGWA. KINEROS2 rainfall input files created outside of AGWA (either uniform or distributed) can be used in AGWA without causing and problems. Methodologies for utilizing radar data to build distributed event rainfall files in AGWA are currently being investigated.

Uniform rainfall input files can be created in AGWA using one of two data sources provided with the tool, or using data entered by the user. Uniform rainfall, although less appropriate for quantitative modeling of individual events, is particularly useful for relative assessment of land cover change. Precipitation data that can be used to generate design storms in AGWA include the NOAA Atlas 2 Precipitation-Frequency Atlas of the Western United States (NOAA, 1973), and a database of return period storms from various locations. Both of these sources are provided with AGWA, and are currently limited to 11 Western States. Return period rainfall depths are converted it to hyetographs using the USDA-SCS (1973) methodology and a type II distribution. The type II distribution is appropriate for deriving the time distribution of rainfall for most of the country, including all of the interior West. Although the NOAA Atlas 2 data can be used anywhere in the western U.S., the database can be easily edited to add data for areas where it is not provided, and has the added advantage of the option to incorporate an area-reduction factor. The third option of using data entered by the user allows design storm data from any region to be used. User defined storms are entered in the form of a hyetograph, thus providing additional flexibility in defining the time-distribution of rainfall.

SWAT: AGWA can generate either uniform or distributed rainfall input files for SWAT. The option to create distributed rainfall files uses Thiessen precipitation weighting to compute the weighted rainfall depth falling on each subwatershed for each day in the simulation period. The user is automatically routed to the dialog for creating either the uniform or distributed rainfall input based on the number of rain gauges with data in a rain gauge point theme that is designated by the user. If there are two or fewer gauges Thiessen polygons cannot be generated and a uniform rainfall input file will be created (using the gauge closest to the watershed centroid if there are two). When there are more than two gauges a distributed input file will be written.

Although any gauge data can be used, National Weather Service gauge data are the most widely available. A point theme of rain gage locations and an unweighted daily precipitation database file are necessary to generate the input file. Missing data can be accommodated through a weighting scheme that dynamically adjusts the gauge weights according to those gauges that do have data for that day.

WATERSHED MODELING WITH AGWA

There are several primary intended uses of AGWA. For one, AGWA can be used in a research environment as a hydrologic modeling tool. In this setting, the user would be expected to alter the look-up tables or estimated parameters manually to allow for more rigorous quantitative assessment. While AGWA is designed to utilize relatively coarse GIS data, it is fully modular, which allows for customization and the rapid alteration of the basic assumptions used to provide parameter estimation. In the absence of a rigorous training set for calibration and validation, AGWA is well suited for watershed assessment using hydrologic response as a metric of change. If multiple land cover scenes are available, a relative assessment of the impacts of land cover change on hydrologic response as a function of time may be accomplished following Miller *et al.* (2002). In the absence of repeat classified imagery, space may be substituted for time and a spatial watershed assessment undertaken to compare watersheds relative to one another.

Preliminary research during the development of AGWA was presented by Hernandez *et al.* (2000). In their study, it was shown that simulated runoff response is sensitive to land cover change in both the SWAT and KINEROS2 models and showed how the assumptions inherent in the look-up tables determines the direction and magnitude of change. For example, land cover change on a homogenous small watershed from desertscrub to mesquite showed only a 6.7% increase in simulated runoff, while a transition to urban resulted in a 46% increase. Their results also demonstrated the impact of calibration and distributed rainfall on model results, both of which significantly increased model efficiency.

Recent research by Miller *et al.* (2002) illustrated the use of AGWA in coordinated ecological and hydrologic assessment. The authors carried out analyses of the ecological changes since the early 1970's within the Upper San Pedro River Basin in southeastern Arizona and the Cannonsville Watershed in the Catskill/Delaware region of New York. AGWA was used to simulate average annual water yield changes with the SWAT model in both study areas. The

Cannonsville watershed was found to have improved its watershed condition (decreased runoff and increased water quality), while the San Pedro was found to have degraded due to increased urbanization and transitions of grassland and desertscrub to mesquite. The regions that were identified as having undergone the greatest hydrologic changes were also identified as high transition areas by the ecological analyses.

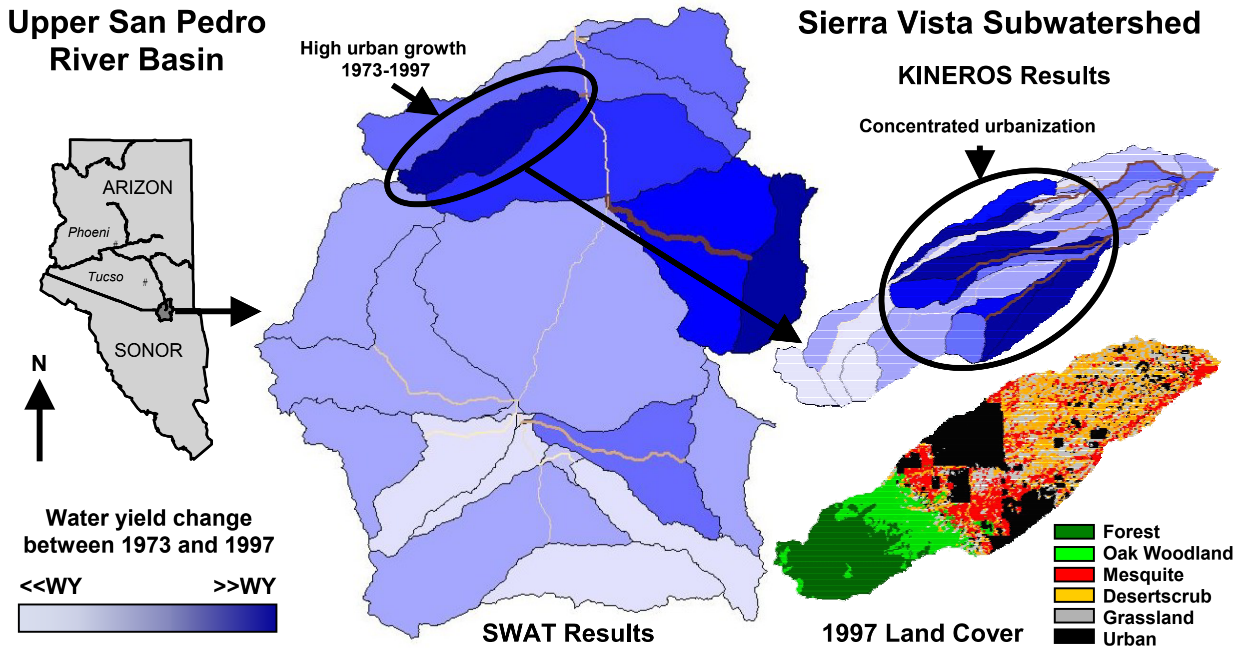

Figure 3. Model results from the upper San Pedro River Basin and Sierra Vista Subwatershed showing the relative increase in simulated water yield as a result of urbanization between 1973 and 1997. Change in water yield for the channels is shown in shades of brown for clarity.

Strong spatial variability was found to exist within the San Pedro Basin, and a highly impacted subwatershed was modeled using KINEROS2 to assess localized changes as a function of return-period rainfall events. In this approach, Miller *et al.* (2002) used a multi-temporal and multi-spatial scale approach to assess land cover change impacts on simulated watershed response and found that localized changes within the San Pedro Basin were found to have significant impacts on simulated runoff volume, peak discharge, and sediment yield (Figure 3). A small watershed near the City of Sierra Vista was identified with the SWAT model as having experienced a high degree of change in average annual runoff. Event runoff from this subwatershed was modeled with KINEROS2 to better define the localized impacts of urbanization and mesquite invasion on runoff and sediment yield. This approach illustrates the use of AGWA in both spatial and temporal scaling studies for assessment of relative change.

CONCLUSIONS

A GIS-based hydrologic modeling toolkit called the Automated Geospatial Watershed Assessment (AGWA) tool has been developed for use in watershed analysis. This tool has been released as open-source and is fully modular and customizable. AGWA automates the process of converting commonly available GIS data to input parameter files for the SWAT and KINEROS2 hydrologic models. Rainfall files for both models can be prepared within AGWA depending on the availability of rainfall data. Results from these models, such as runoff, peak discharge, and sediment yield for each model element, are imported into AGWA and can be investigated using a suite of visualization tools. Since the models operate at different spatial and temporal scales, they provide the ability to perform a range of analyses as a function of research or management objectives.

Because AGWA is designed to convert generic GIS data, it can be applied on ungauged watersheds. However, in the absence of a calibration/validation exercise, results are best suited for relative analysis. Given repeat classified remote sensing imagery, AGWA provides the capability to assess the spatial distribution of the impacts of land cover change on watershed hydrologic response. In the absence of repeat imagery, AGWA may be used to identify portions of a study area susceptible to change or high priority management zones.

Current research regarding the effects of remote sensing classification error and the impact of geometric complexity on simulated response will provide estimates of uncertainty associated with using AGWA in an application setting. Future research will focus on the application of AGWA in a range of hydrologic settings through the use of historical data to ensure that the tool can be widely applied with confidence under a range of conditions.

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